ENERGETICS OF A LONG-IMPLOSION-TIME, 12-CM-DIAMETER ARGON-GAS-PUFF Z PINCH AT 6.5 MA*

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Abstract

We carry out an energy-inventory analysis for a 12-cm-diameter, argon gas-puff shot on the Saturn generator. From the measured pinch inductance time history, we infer the average radius of the pinch current, r_{ind}, and the total work done on the pinch, $E_{coupled}$, both as functions of time. The kinetic energy as a function of time, E_{KE}, is inferred from r_{ind} and the measured initial mass distribution, assuming all of the mass is accreted as in a snowplow. The results show that early in the implosion, $E_{coupled} \approx E_{KE}$. However, when the pinch begins to radiate significantly, E_{KE} begins to decrease while $E_{coupled}$ continues to increase. The increase in coupled energy goes into plasma internal energy, E_{int}, i.e., ionization and thermal energies of the z-pinch plasma, and total radiation, E_{rad}. During the time of K-shell emission, the significant (~ 150-kJ) increase in $E_{coupled}$ is reflected in approximately the same increase in E_{rad}. There is agreement between E_{int} at the time of peak K-shell emission inferred from $E_{coupled}$ and measurements of E_{rad}, and E_{int} inferred from independent spectroscopic measurements combined with an atomic-physics model.

I. Introduction

We wish to maximize the K-shell yield from high-atomic-number, gas-puff z pinches, e.g., K-shell energy of ~ 1 – 8 keV, and to develop z-pinch-based concepts for sources of higher photon energy (up to 40 keV). To this end, large-diameter implosions [1-8} are needed to: (a) produce the high specific energy required to excite K-shell line radiation from high-atomic-number z pinches, (b) properly match the load to high-current (~ 10 MA and higher) generators [9-12], and (c) develop continuum-radiator concepts [13-15] that might require ionizing beyond the optimum He/H-like state for K-shell emission. Large-initial-diameter implosions are also required for efficient coupling between the z pinch and a generator with a long current rise time (> 100 ns) and, thus, a desirable lower driving voltage. It has been shown for gas-puff z-pinches both theoretically [16-18] and experimentally [7,19-21] that the expected deleterious effects on final pinch formation associated with the increase in the Rayleigh-Taylor instability growth at larger diameter can be mitigated by using an initial mass profile that is peaked on axis.

An important aspect of z-pinch physics is obtaining an understanding of the pinch energetics. For example, work with wire arrays suggested that more energy is radiated than can be accounted for by one-dimensional implosion calculations of kinetic energy that assume the mass resides in a thin shell.[22] A higher-than-expected resistivity was one proposed explanation for this observation. As noted in previous simulations of wire arrays, the total work done on the pinch plasma by the Lorenz force can far exceed the kinetic energy.[23] Investigations into the energetics of wire arrays continue.[24,25]

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14. ABSTRACT
We carry out an energy-inventory analysis for a 12-cmdiameter, argon gas-puff shot on the Saturn generator. From the measured pinch inductance time history, we infer the average radius of the pinch current, rind, and the total work done on the pinch, Ecoupled, both as functions of time. The kinetic energy as a function of time, EKE, is inferred from rind and the measured initial mass distribution, assuming all of the mass is accreted as in a snowplow. The results show that early in the implosion, Ecoupled ¡Ö EKE. However, when the pinch begins to radiate significantly, EKE begins to decrease while Ecoupled continues to increase. The increase in coupled energy goes into plasma internal energy, Eint, i.e., ionization and thermal energies of the z-pinch plasma, and total radiation, Erad. During the time of K-shell emission, the significant (~ 150-kJ) increase in Ecoupled is reflected in approximately the same increase in Erad. There is agreement between Eint at the time of peak K-shell emission inferred from Ecoupled and measurements of Erad, and Eint inferred from independent spectroscopic measurements combined with an atomic-physics model.

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For the gas-puff implosions with structured radial profiles studied here, the thin-shell approximation is clearly not appropriate. Moreover, the fact that the initial mass is distributed in radius also calls into question the role of kinetic energy in the overall pinch energetics, as much of the mass is not initially at large radius. The transfer of energy from ions to electrons during the stagnation of a neon gas-puff z-pinch has been studied.[26] However, the global energy inventory for large diameter gas-puff z pinches has not been explored.

In this paper, we focus on Saturn shot 3565, which was one of several taken during the first experiments on Saturn with a 12-cm diameter, triple-shell, argon gas puff. This particular shot was chosen because all the diagnostic signals were available and a full analysis was possible. Also, this was the only shot in the series for which the vacuum voltmeter was well calibrated and properly shielded,[27] allowing for the first time a reliable determination of the voltage driving the gas puff as a function of time. As will be seen, this is a critical measurement for determining the overall energy inventory. From this inventory, the plasma internal energy, which is the sum of the thermal and ionization energies of the pinch plasma, is inferred. The internal energy so inferred is compared to the internal energy obtained independently from spectroscopic measurements and an atomic physics model. Knowledge of the initial mass distribution also is critical for these analyses.

The details of the experimental configuration and description of the energy-inventory analysis are given in Section II. In Section III we present data and analyses for the overall energy inventory of Saturn shot 3565. In Section IV, the internal energy near the time of peak K-shell power obtained from the energy inventory is compared to that obtained from the measured spectral characteristics in combination with an atomic physics model. The work is summarized in Section V.

II. EXPERIMENTAL SETUP AND DESCRIPTION OF ANALYSIS

The work reported herein was performed on the Saturn generator,[28] located at Sandia National Laboratories. For this work, the posthole convolute diameter was increased from 15 cm to 30 cm.[29] Also, the Saturn pulse-forming line was shorted out to provide the "long-pulse" mode, where the current rise time into a short circuit load is ~ 230 ns. The gas-puff nozzle is a 12-cm diameter, triple-shell nozzle illustrated in Fig. 1.[7,19,20] The initial gas mass distribution is measured using the planar, laser-induced fluorescence (PLIF) method.[30,31] For Saturn shot 3565, the three plenums were pressurized as follows: outer = 3.3 psia, inner = 10.0 psia, center jet = 72.0 psia. This combination resulted in nominal average mass/length of 425 μg/cm with an uncertainty of ±15% and a radial distribution that is peaked on axis.[7,19] The latter is essential for achieving high-quality implosions from large radius. The radiation diagnostics include a bare bolometer (nickel element, corrected for K-transparency) to measure the total radiated energy, filtered calorimeters to measure the K-shell yield, and a variety of photo-conductive devices (PCDs) filtered to measure the argon K-shell time history. For this work, the PCDs were normalized to the calorimeters. A K-shell, time-integrated image of the pinch is obtained from an appropriately filtered CCD-based pinhole camera. Argon K-spectra and the K-spectra from a chlorine dopant (Freon), introduced in either the center jet or inner shell on various shots, are measured using a CCD-based crystal spectrograph. The L-shell radiation is inferred from a filtered x-ray diode normalized to a bolometer.

The current is determined by subtracting and averaging the signals from two, oppositely wound B-dots 180° apart in azimuth and located between the posthole convolute and the gas-puff z-pinch. The voltage driving the gas puff is directly measured using a vacuum voltmeter[32] The implementation of this diagnostic on Saturn is described in detail in Ref 27.

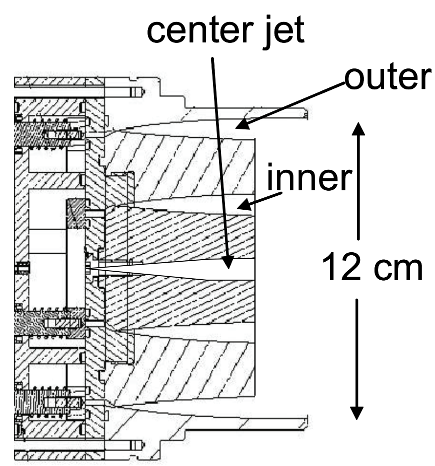

Figure 1. Cross section of the 12-cm diameter, triple nozzle used on Saturn shot 3565.

Figure 2 gives the current and K-shell x-ray power as functions of time for Saturn Shot 3565. The peak current is 6.5 MA and the implosion time is 206 ns. The energy radiated from the K-shell for this shot is 72 kJ, roughly twice what was previously obtained at shorter implosion time (~ 50 ns) using a smaller-diameter (~ few cm) gas-puff.[20,33]

The total energy delivered to the z-pinch plasma from the electrical circuit, $E_{coupled}$, is given by[27]

$$E_{coupled}(t) = \int_0^t IVdt' - \frac{1}{2}LI^2 = \frac{1}{2}\int_0^t \left(\frac{dL}{dt}\right) I^2 dt' \quad (1),$$

where I and V are the z-pinch current and driving voltage, respectively, and L is the z-pinch inductance. In Eq. (1), we have assumed that that resistance is negligible. The change in L, ΔL, can be expressed as:

$$\Delta L(nH) = L(t) - L_0 = 2 \times l(cm) \times \ln\left(\frac{r_0}{r_{ind}(t)}\right) \quad (2).$$

Here L_0 is the fixed inductance associated with the region between the location where the voltage is measured and the initial z-pinch, l is the pinch length (3.8 cm for this work), r_{ind} is the axially-averaged effective radius of the pinch current, and, again assuming resistance is negligible, L(t) is given by

$$L(t) = \frac{\int V(t)dt}{I(t)} \quad (3).$$

$E_{coupled}$ is the total work done on the plasma and can be expressed as

$$E_{coupled}(t) = E_{KE} + E_{int} + E_{rad} \quad (4),$$

where E_{KE} is the kinetic energy associated with the radially-directed pinch implosion and E_{rad} is the total radiated energy. The internal energy, E_{int} is given by

$$E_{int} = E_{ionize} + \frac{3}{2} N_i \left[kT_i + ZkT_e\right] \quad (5),$$

where Z is the is the average ionization state of the pinch plasma, N_i is the total number of ions in the pinch, k is Boltzman's constant, T_i (T_e) and is the ion (electron) temperature, and E_{ionize} (a well known function of Z) is the energy required to ionize up to the ionization state Z. The second term on the right-hand side of Eq. (5) represents the plasma thermal energy associated with random motion. For this work, $E_{KE}(t)$ is obtained using $d(r_{ind})/dt$ for the radial speed and the measured initial mass distribution to determine the mass accreted up to $r_{ind}(t)$ with $d(r_{ind})/dt$, so that

$$E_{KE}(t) = \frac{1}{2} m_{accret}(t) \left(\frac{dr_{ind}}{dt}\right)^2 \quad (6),$$

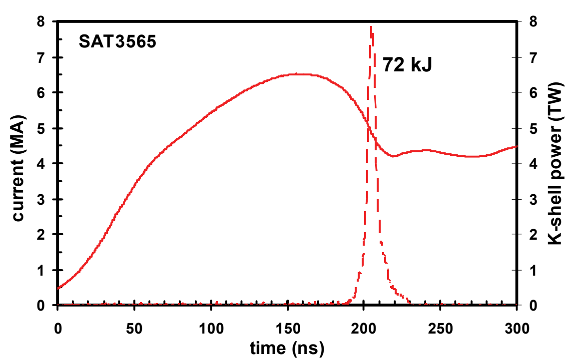

Figure 2 Plot of current and K-shell power as functions of time.

where m_{accret} is the total mass accreted up to r_{ind} at time t.

III MEASUREMENTS AND ANALYSIS FOR ENERGY INVENTORY

Plotted in Figure 3 are the pinch current, K-shell power, and r_{ind} obtained from Eq. (2), all as functions of time. Also shown are two radii from a 0-D snowplow calculation, r_{sp}, using the measured current and measured initial mass distribution with two total masses, 361 μg/cm (within the measurement uncertainty) and 425 μg/cm (nominal). In general, the snowplow calculation suggests that the independently measured mass, current, and implosion time are consistent. Using 361 μg/cm gives a better match to the 206-ns implosion time. Also note that the r_{sp} is continually accelerating through stagnation while r_{ind} decelerates. This is probably a consequence of the snowplow calculation not accounting for the plasma pressure. Unlike r_{sp}, the implosion speed given by $d(r_{ind})/dt$ is remarkably constant, ~ 46 cm/μs. This constant speed implies that, on average, the radial acceleration is very small (a result of the initial radially distributed mass distribution), suggesting that the Raleigh-Taylor growth is mitigated. The initial radius for the snowplow calculation, 8.3 cm, was chosen based on the largest radius for which there are PLIF data. More sensitive measurements have shown the presence of gas at large radii in similar nozzles.[34] The 8.3-cm radius is

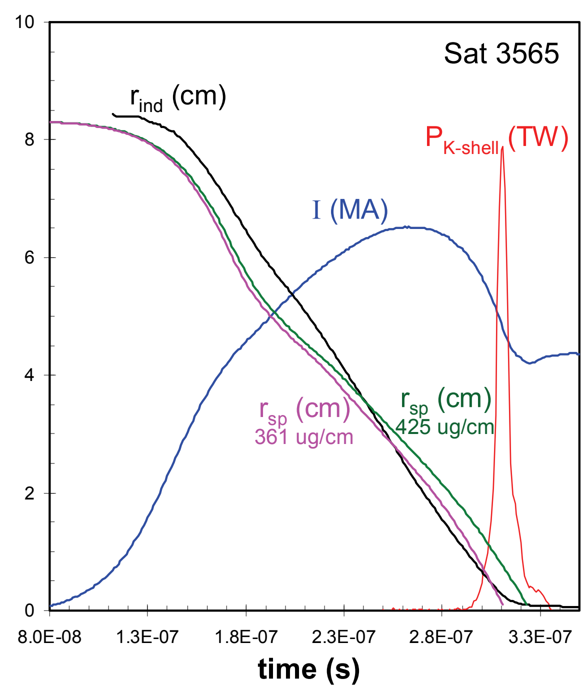

Figure 3 Plot of pinch current, K-shell power and r_{ind} from Eq (2). Also shown are two radii, r_{sp}, calculated using the 0-D snowplow model with the pinch current and measured initial density distribution for two different total masses as inputs.

very close to the initial value of r_{ind}. However, both are very close to the return current post radius of 8.6 cm. All of this suggests that the initial current path might not be purely axial, but have a significant radial component that results in the initial current-sheath motion having a component in the axial direction.[35]

$E_{coupled}$ from Eq. (1) along with E_{KE} from Eq. (5) are shown in Fig. 4 along with the pinch current and K-shell power, all as functions of time. Early in the implosion, $E_{coupled} \approx E_{KE}$. Because the implosion speed is nearly constant, the increase in E_{KE} is a result of mass accretion. At $r_{ind} \approx 2.3$ cm, when $E_{coupled} \approx 150$ kJ, E_{KE} begins to decrease as the pinch begins to slow down. This is about the time the total radiation becomes appreciable (see Fig. 5). The rate of slowing down more than compensates for the small but finite mass accretion at small radius. As E_{KE} begins to decrease, however, $E_{coupled}$ continues to increase over the next ~ 70 ns to 440 kJ at the time of peak K-shell power. Also plotted in Fig. 4 is $E_{coupled} - E_{KE} = E_{int} + E_{rad}$ (see Eq. [4]). Near the time of peak K-shell power, E_{KE} has decreased nearly to zero and $E_{coupled} = E_{int} + E_{rad}$.

The total radiated energy, E_{rad}, is plotted on an expanded time scale in Fig. 5, along with the pinch current, K-shell power, and $E_{coupled}$. During the time of K-shell emission, $E_{coupled}$ increases by 150 kJ, from 350 kJ to 500 kJ, showing that energy continues to be delivered to the pinch during stagnation. During that same time interval, the total radiation increases by nearly the same amount, 140 kJ, and the total K-shell yield is 72 kJ. A significant increase in coupled energy during the time of

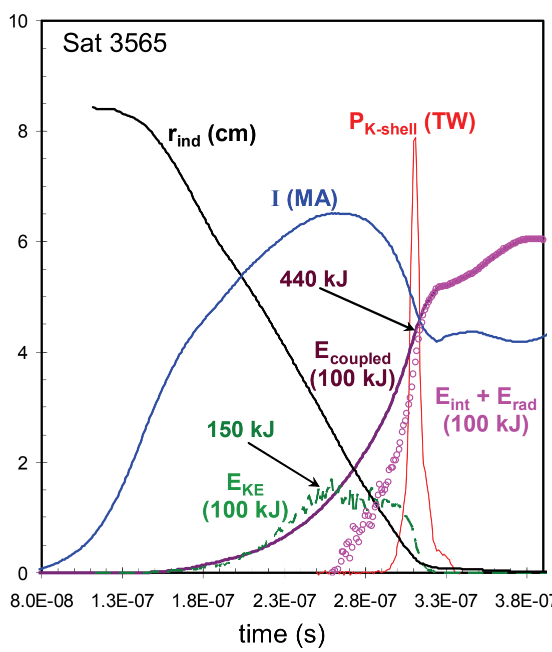

Figure 4 Plot of $E_{coupled}$ and E_{KE} as functions of time along with pinch current, K-shell power and r_{ind} all as functions of time. At time of peak K-shell power, $E_{coupled} = E_{int} + E_{rad}$

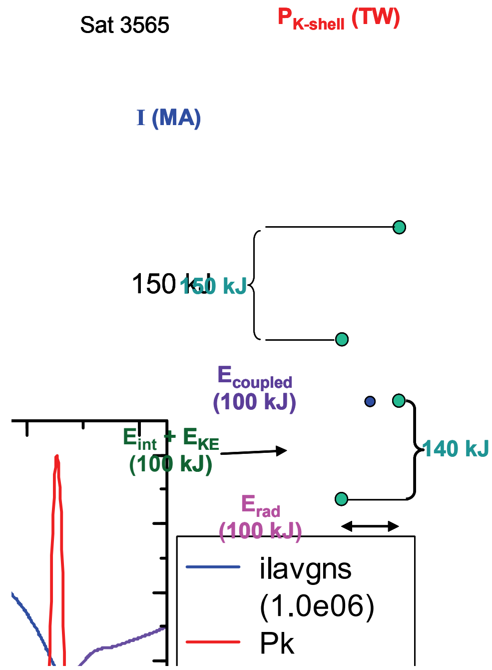

Figure 5 Plot of $E_{coupled}$ and E_{rad} as functions of time along with pinch current and K-shell power. During the time of K-shell emission, $E_{int} \approx E_{coupled} - E_{rad} \approx$ constant, 250 kJ.

K-shell emission also was observed in a neon gas-puff z-pinch pinch where a vacuum voltmeter was first used to obtain the coupled energy.[36] As noted above (see Fig. 4), E_{KE} drops to near zero during the K-shell emission. Thus, from Eq. (4), $E_{int} \approx E_{coupled} - E_{rad}$. and as seen in Fig. 4, E_{int} is constant at about 250 kJ, during this time. Thus a steady state of sorts is established during the time of K-shell emission, with the coupled energy going into radiated energy and the internal energy remaining fixed. The process is not direct, however. It is thought that the higher temperature ions transfer energy to electrons which then lose their energy via radiation.

In the next section, we compare E_{int} determined from electrical and total radiation measurements at the time of peak K-shell power (250 kJ), with the internal energy at that time obtained from independent spectroscopic diagnostics in combination with an atomic physics model.

IV SPECTROSCOPIC DETERMINATION OF INTERNAL ENERGY

Using a well known technique,[37,38] the argon K-shell spectra can be used to obtain the radially-integrated axially-averaged T_e. The argon atomic model used in this technique has been improved and now includes detailed level structure for all 18 ionization stages of argon, a total of 185 atomic levels. The radiation transport equations are solved for 611 lines with 10 to 25 photon energy

points per line. The same procedure is applied to the chlorine K-shell spectra to obtain a radially localized T_e near the time of peak K-shell power in a central region (Freon in the center jet) or an inner region (Freon in the inner shell). Knowledge of T_e, combined with the absolute K-shell power and measurement of the K-shell emitting region is used to obtain the ion density near the time of peak K-shell power, n_i.[37,38] This analysis reveals for Saturn shot 3565 that T_e in the central and inner regions is 1.9 and 1.4 keV, respectively. In addition, 44% of the initial mass is radiating in the K-shell from a region of 1.15 mm in radius, with $n_i = 7\text{x}10^{19}$ cm^{-3}.

Based on these measured quantities, we construct a 3-radial-zone model for the stagnated pinch plasma in which the two central zones, zone 1 (central) and zone 2 (inner) radiate in the K-shell with two different Te's and with mass ratio given by the measured initial injected mass ratio between the nozzle center jet and the inner shell, 1:2. The two central zones are surrounded by a colder blanket, zone 3, that comprises the remainder of the mass, 56% of the initial mass, and radiates only in the L-shell. The measured L-shell power at the time of peak K-shell emission, 4 TW/cm, is used with the argon atomic physics model to infer the ion density and thus the radius associated with the L-shell radiating region. We assume the electron temperature in the outer zone is 0.7 keV (half of T_e in zone 2). We have no measurement of T_i, so we assume, based on previous z-pinch experiments where T_i was measured, that $T_i \approx 20$ keV in all three zones. Note that if one equates the ion kinetic energy to a thermal energy of $3T_i/2$, assuming the observed 46 cm/μs radial velocity, one obtains $T_i = 28$ keV as an upper bound to T_i. Thus, the assumption for T_i is quite reasonable. The atomic physics model self-consistently determines Z for the given plasma conditions.

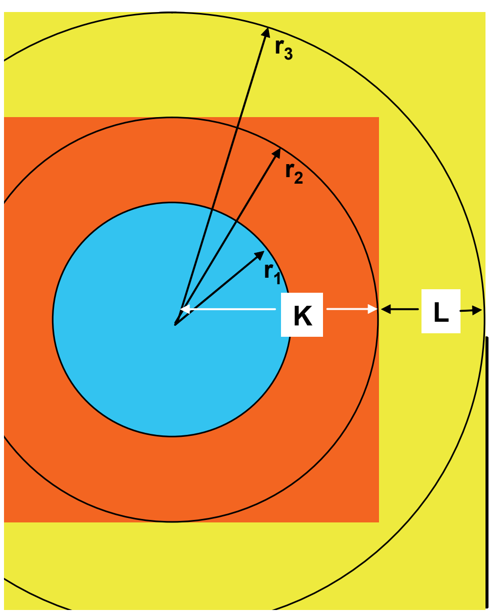

Figure 6 Schematic and table for the three-zone model. Parameters in orange are not inferred from measured quantities.

Figure 6 summarizes the three-zone model, measurements, and assumptions described above. Recalling Eq. (5) for E_{int}, we can see from Fig. (6) that the total internal energy can be calculated from summing across the three zones. This method gives 252 kJ for the total internal energy at the time of peak K-shell emission compared with 250 kJ determined from the energy inventory (see Fig. 5 and accompanying text). While there are many assumptions, this is quite remarkable agreement. In future experiments, attempts will be made to reduce the uncertainties in this approach.

III. SUMMARY

We have carried out an energy inventory analysis for a 12-cm-diameter, argon gas-puff shot on the Saturn generator with a peak current of 6.5 MA and an implosion time of 206 ns. This resulted in 72 kJ of argon K-shell radiation, about a factor of 2 more than previously obtained on Saturn using smaller diameter nozzles and at shorter implosion times. Using the measured current and voltage, we determine $E_{coupled}$, the total work done on the pinch plasma, and the pinch inductance time history, from which we infer the axially averaged radius of the pinch current, r_{ind}, both as functions of time. The kinetic energy as a function of time, E_{KE}, is inferred from r_{ind} and the measured initial mass distribution, assuming all the mass is accreted as in a snowplow. The results show that early in the implosion, $E_{coupled} \approx E_{KE}$. However, when the $E_{coupled} \approx 150$ kJ, $r_{ind} \approx 2.3$ cm, and the pinch begins to radiate significantly, E_{KE} begins to decrease while $E_{coupled}$ continues to increase. Over the next ~ 70 ns, E_{KE} becomes negligible while $E_{coupled}$ increases to 440 kJ at the time of peak power. The increase in coupled energy goes into E_{int} and E_{rad}. During the time of K-shell emission, $E_{coupled}$ increases by 150 kJ, showing that significant amount of energy continues to be delivered to the pinch during stagnation. This increase in $E_{coupled}$ is reflected in approximately the same increase in E_{rad}, with $E_{int} \approx$ constant (250 kJ), suggesting a steady state where $E_{coupled}$ is rapidly radiated away. There is agreement between the value E_{int} at the time of peak K-shell emission inferred from $E_{coupled}$ and measurements of E_{rad}, and E_{int} inferred from independent spectroscopic measurements combined with an atomic physics model. This agreement helps to confirm our approach to the energy-inventory analysis. It is interesting to note that because wire arrays rapidly transform from a line mass to a distributed mass, the conclusions reached in this gas-puff work may apply to wire arrays as well.

Measurement of the pinch driving voltage is an essential part of carrying out this energy inventory. We hope to apply this approach, with improved current and radiation diagnostics, to future experiments on Saturn.

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VI REFERENCES

1. P. Coleman, J. Rauch, W. Rix, J. Thompson and R. Wilson, "Recent ACE 4 Z-pinch experiments: long implosion time argon loads, uniform fill versus annular shell distributions and the Rayleigh-Taylor instability problem," in *Fourth Int. Conf. on Dense Z Pinches*, Vancouver, Canada, May 1997. Woodbury, New York: *AIP Conf. Proc. 409*, pp. 119-123.
2. A.V. Shishlov, R.B. Baksht, A.V. Fedunin, F.I. Fursov, B.M. Kovalchuk, V.A. Kokshenev, N.E. Kurmaev, A.Yu. Labetsky, V.I. Oreshkin, A.G. Russkikh, A. Fisher, B. Moosman, and B.V. Weber "Long time implosion experiments with double gas puffs," *Phys. Plasmas*, vol. 7, pp. 1252-1262, April 2000.
3. H. Sze, P.L. Coleman, J. Banister, B.H. Failor, A. Fisher, J.S. Levine, Y. Song, E.M. Waisman, J.P. Apruzese, R.W. Clark, J. Davis, D. Mosher, J.W. Thornhill, A.L. Velikovich, B.V. Weber, C. A. Coverdale, C. Deeney, T.L. Gilliland J. McGurn, R.B. Spielman, K.W. Struve, W.A. Stygar, and D. Bell, "Efficient argon K-shell radiation from a Z-pinch at currents > 15 MA," *Phys. Plasmas*, vol. 8, pp. 3135-3138, July 2001.
4. R. Davis, B.V. Weber, J.P. Apruzese, J.W. Thornhill, A. Velikovich, M. Krishnan, P. Coleman, H. Sze, J. Levine, Y. Maron, and I. Vitkovitsky, "Recent progress in DoD's program to develop Ar K-shell x-ray radiation sources," in *Proc. 14th IEEE Int. Pulsed Power Conf.*, Dallas, Texas, June 2003, pp. 37-41, IEEE Catalog No. 03CH37472.
5. J.S. Levine, J.W. Banister, B.H. Failor, N. Qi, Y. Song, H.M. Sze and A. Fisher, "Long implosion time (240 ns) Z-pinch experiments with a large diameter (12 cm) double-shell nozzle," *Phys. Plasmas,* vol. 11, pp. 2054-2059, May 2004.
6. R.J. Commisso, J.P. Apruzese, Y.K. Chong, J. Davis, M. H. Frese, D. Mosher, D.P. Murphy, D.G. Phipps, J.W. Thornhill, A.L. Velikovich, B.V. Weber, F.C Young, J.W. Banister, B.H. Failor, J.S. Levine, N. Qi, H. Sze, A. Bixler, P. Coleman, M. Krishnan, J. Thompson, E. Carlson, R.C. Hazelton, E.J. Yadlowsky, F. Davies, and C. De LaCruz, "Overview of recent large-diameter, gas-puff Z-pinch research," in *Conf. Record - Abstracts 2005 IEEE Int. Conf. on Plasma Science*, Monterey, California, June 2005, p.272, IEEE Catalogue No. 05CH37707.
7. H. Sze, J. Banister, B.H. Failor, J.S. Levine, N. Qi, A.L. Velikovich, J. Davis, D. Lojewski, and P. Sincerny, "Efficient radiation production in long implosions of structured gas-puff Z pinch loads from large initial radius," *Phys. Rev. Lett.*, vol. 95, pp. 105001-1-105001-4, September 2005.
8. P. Coleman, A. Bixler; A. Gerhan, J. Knight, S. Lee, M. Krishnan, J. Thompson, K. Wilson, and H. Ross, "Continued development of a 12-cm diameter nozzle for argon Z-pinches," *IEEE Trans. Plasma Sci.*, vol. 23, pp. 729-762, April 2005.
9. J.W. Thornhill, K.G. Whitney, and J. Davis, "Transition from I^4 to I^2 scaling of K-shell emission in aluminum array implosions," *J. Quant. Spectrosc. Radiat. Transfer*, vol. 44, no. 2, pp. 251-259, 1990.
10. J.W. Thornhill, K.G. Whitney, J. Davis, and J.P. Apruzese, "Investigation of K-shell emission from moderate-Z, low-η (-velocity), Z-pinch implosions," *J. Appl. Phys.*, vol. 80, pp. 710-718, July 1996.
11. D. Mosher, N. Qi, M. Krishnan, "A two-level model for K-shell radiation scaling of the imploding Z-pinch plasma radiation source," *IEEE Trans. Plasma Sci.*, vol. 26, pp. 1052-1061, June 1998.
12. D. Mosher, M. Krishnan, N. Qi, P.L. Coleman, E.M. Waisman, and H. Sze, "Current scaling of optimum K-shell x-ray yield and load mass applied to argon gas-puff Z-pinches," in *Proc. 13th IEEE Int. Pulsed Power Conf* ., Las Vegas, Nevada, June 2001, pp. 277-280, IEEE Catalog No. 01CH37251.
13. A. L. Velikovich, J. Davis, V. I. Oreshkin, J. P. Apruzese, R. W. Clark, J. W. Thornhill, and L. I. Rudakov, "High energy photon radiation from a Z-pinch plasma," *Phys. Plasmas*, vol. 8, pp. 4509-4517, October 2001.
14. F C. Young, R.J. Commisso, D. P. Murphy, J. P. Apruzese, D. Mosher, A. L. Velikovich, P. L. Coleman, J. W. Banister, B. H. Failor, J. S. Levine, N. Qi, and H. M. Sze, "Measurement and Analysis of Continuum Radiation from a Large-Diameter, Long-Implosion-Time, Argon Gas-Puff Z-Pinch at 6 MA,: *IEEE Trans Plasma Sci.* vol. 34, 2312 – 2324, October 2006.
15. P.L. Coleman, J.P. Apruzese, A.L. Velikovich, J.W. Thornhill, J. Davis, C. Coverdale, J.S. Levine, B. Failor, H. Sze, and J. Banister, "Measurement of the argon spectrum from ~0.1 to >10 keV for a Z-pinch at the 15 MA level," *IEEE Trans. Plasma Sci.*, vol. 35, 31-42, February 2007.
16. A.L. Velikovich, et al., *Phys. Rev. Lett.* **77**, 853 (1996) and *Phys. Plasmas* **5**, 3377, 1998.
17. J.H. Hammer, et al., *Phys. Plasmas* **3**, 2063, 1996.
18. A. S. Chuvatin, L. I. Rudakov, A. L. Velikovich, J. Davis, and V. I. Oreshkin, *IEEE Trans. Plasma Sci.* vol. 33, 739, 2005.
19. J.S. Levine, J.W. Banister, B.H. Failor, N. Qi, and H.M. Sze, A.L. Velikovich, R. J. Commisso, J. Davis, D. Lojewski, "Implosion dynamics and radiative characteristics of a high yield structured gas puff load," *Phys. Plasmas* vol. 13, 082702, 2006; and references therein.

20. H. Sze, J.S. Levine, J. Banister, B.H. Failor, N. Qi, P. Steen, A.L. Velikovich, J. Davis, and A. Wilson, “Magnetic Rayleigh-Taylor Instability Mitigation and Efficient Radiation Production in Gas Puff Z-Pinch Implosions,” *Phys Plasmas*, 14, 056307, 2007.
21. J. W. Thornhill, Y. K. Chong, J. P. Apruzese, J. Davis, R. W. Clark, J. L. Giuliani, Jr., R. E. Terry, A. L. Velikovich, and R. J. Commisso, K. G. Whitney, M. H. Frese and S. D. Frese, J. S. Levine, N. Qi, and H. Sze, P. L. Coleman, C. A. Coverdale, and B. Jones, C. Deeney, “One- and Two-Dimensional Modeling of Argon K-Shell Emission from Gas-Puff Z-Pinch Plasmas,” *Phys. Plasmas* vol. 14, 063301, 2007.
22. C. Deeney, C. A. Coverdale, M. R. Douglas, K. W. Struve, R. B. Spielman, W. A. Stygar, D. L. Peterson, and N. F. Roderick, “Radiative properties of high wire number tungsten arrays with implosion times up to 250 ns,” *Phys. Plasmas* vol. 6, 3576 (1999).
23. D.L. Peterson, R.L. Bowers, K.D. McLenithan, C.Deeney, G.A. Chandler, R. B. Spielman, and M. K. Matzen, “Characterization of energy flow and instability development in two-dimensional simulations of hollow Z pinches,” *Phys. Plasmas* vol. 5, 3308 – 3310 (September 1998)
24. D.B. Sinars, M.E. Cuneo, R.W. Lemke, E.M. Waisman, B. Jones, M. Jones, J.L. Porter, S. V. Lebedev, “Empirical Determination of Radiation Energetics of Inertial Confinement Fusion Relevant Wire-Array Z-Pinches,” this conference, paper 2D2.
25. B. Jones, C.A. Jennings, M.E. Cuneo, D.B. Sinars, G. A. Rochau, J.E. Bailey, K. Peterson, C.A. Coverdale, and Y. Maron, “Measurement of Plasma Temperature and Density Profiles, Implosion Velocity, and Kinetic Energy in Wire Array Z Pinches,” this conference, paper 3P107.
26. E. Kroupp, D. Osin, A. Starobinets, V. Fisher, V. Bernshtam, and Y. Maron, *Phys. Rev. Lett.* Vol. 98, pp. 115001-1 – 115001-4, March 2007.
27. D.P. Murphy, B.V. Weber, R.J. Commisso, J.P. Apruzese, and D. Mosher, “Time Resolved voltage Measurements of Imploding Radiation Sources at 6 MA with a Vacuum Voltmeter,” this conference, paper 3D3.
28. D.D. Bloomquist, R.W. Stinnett, D.H. McDaniel, J.R. Lee, A.W. Sharpe, J.A. Halbleib L.G. Schlitt, P.W. Spence, and P. Corcoran, “Saturn, a Large Area X-Ray Simulation Accelerator,” Proceedings of the 6th IEEEE Pulsed Power Conference, Arlington VA, 1987, P.J. Turchi and B.H. Bernstein, eds. IEEE Cat. No. 87CH2522-1 pp. 310-317.
29. C.A. Coverdale, K. Mikkelson, C. Deeney, R.B. Spielman, B. Peyton, E. Herrera, P.D. LePell, J. Banister, J. Levine, B. Failor, R. Commisso, D. Murphy, B.V. Weber, J.W. Thornhill, J.P. Apruzese, A.L. Velikovich, J. Davis, P. Coleman, J. Knight, D. Lojewski. “A 12” Diameter Convolute Hardware at Saturn: Design, Assessment, and First Results,” 2007 HEART Conference, San Diego, CA, paper PF.2.
30. B.H. Failor, S. Chantrenne, P.L. Coleman, J.S. Levine, Y. Song, and H.M. Sze, “Proof-of principle laser induced fluorescence measurements of gas distributions from supersonic nozzles,” *Rev. Sci. Instrum.*, vol. 74, pp. 1070-1076, February 2003.
31. N. Qi, B.H. Failor, J. Banister, J.S. Levine, H.M. Sze, and D. Lojewski, “Two-dimensional gas density and velocity distributions of a 12-cm-diameter, triple-nozzle argon Z-pinch load,” *IEEE Trans. Plasma Sci.*, vol. 33, pp. 752-762, (April 2005).
32. D.G. Pellinen and M.S. DiCapua, “Two Megavolt Divider for Pulsed High Voltages in Vacuum,” *Rev. Sci. Instrum.*, Vol. 51, pp. 70 - 73 (January 1980).
33. R.J. Commisso, J. Davis, D. Mosher, D.P. Murphy, J.W. Thornhill, A.L. Velikovich, B.V. Weber, F.C. Young, J.W. Banister, B.H. Failor, J.S. Levine, N. Qi, H.M. Sze, A. Bixler, P.L. Coleman, A. Jarema, J. Knight, S. Lee, M. Krishnan, J. Thompson, and K. Wilson, C.A. Coverdale, C. Deeney, and D. Lojewski, “Increased K-shell Output from 12-cm Diameter, Argon Gas-Puff Z- Pinches at ~ 6-MA on the Decade Quad and Saturn Generators,” 2007 HEART Conference, San Diego, CA, paper F.6.
34. B.V. Weber, B. Moosman and Y. Song, “Gas Distribution Measurements for Double-EAGLE PRS Experiments, Pulsed Power Physics Branch Technote #99-01 (30 April 1999).
35. J. Thompson, P. Coleman, D. Parks, S. Lee, R. Allen, R. Commisso, B. Weber, N. Qi, A. Verma, and M. Scott, “PRS Load B-Dot Current Measurements on Argon Z-Pinches,” 2005 IEEE International Conference on Plasma Science (Monterey, CA, June 2005), IEEE cat. no. 05CH37707, p. 139.
36. D. Mosher, R.J. Commisso, D.P. Murphy, D.G. Phipps, S.J. Stephanakis, B.V. Weber, and F.C. Young,” “Peak Implosion Power as a Predictor of Plasma Radiation Source K-Shell Performance,” Proceedings of the 15th IEEE International Pulsed Power Conference, (Monterey, CA, June 2005), John Maenchen and Edl Schamiloglu, eds., p. 393.
37. J. P. Apruzese, K. G. Whitney, J. Davis, and P. C. Kepple, “K-shell line ratios and powers for diagnosing cylindrical plasmas of neon, aluminum, argon, and titanium,” *J. Quant. Spectrosc. Radiat. Transfer*, vol. 57, no. 1, pp. 41-61, 1997.
38. M.C. Coulter, K.G. Whitney, and J.W. Thornhill, “A new procedure for analyzing x-ray spectra from laboratory plasmas,” *J. Quant. Spectrosc. Radiat. Transfer*, vol. 44, pp. 443-456, 1990.